Study QCD Phase Structure in STAR Experiment

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Outline

(1) Introduction

- Physics programs at STAR

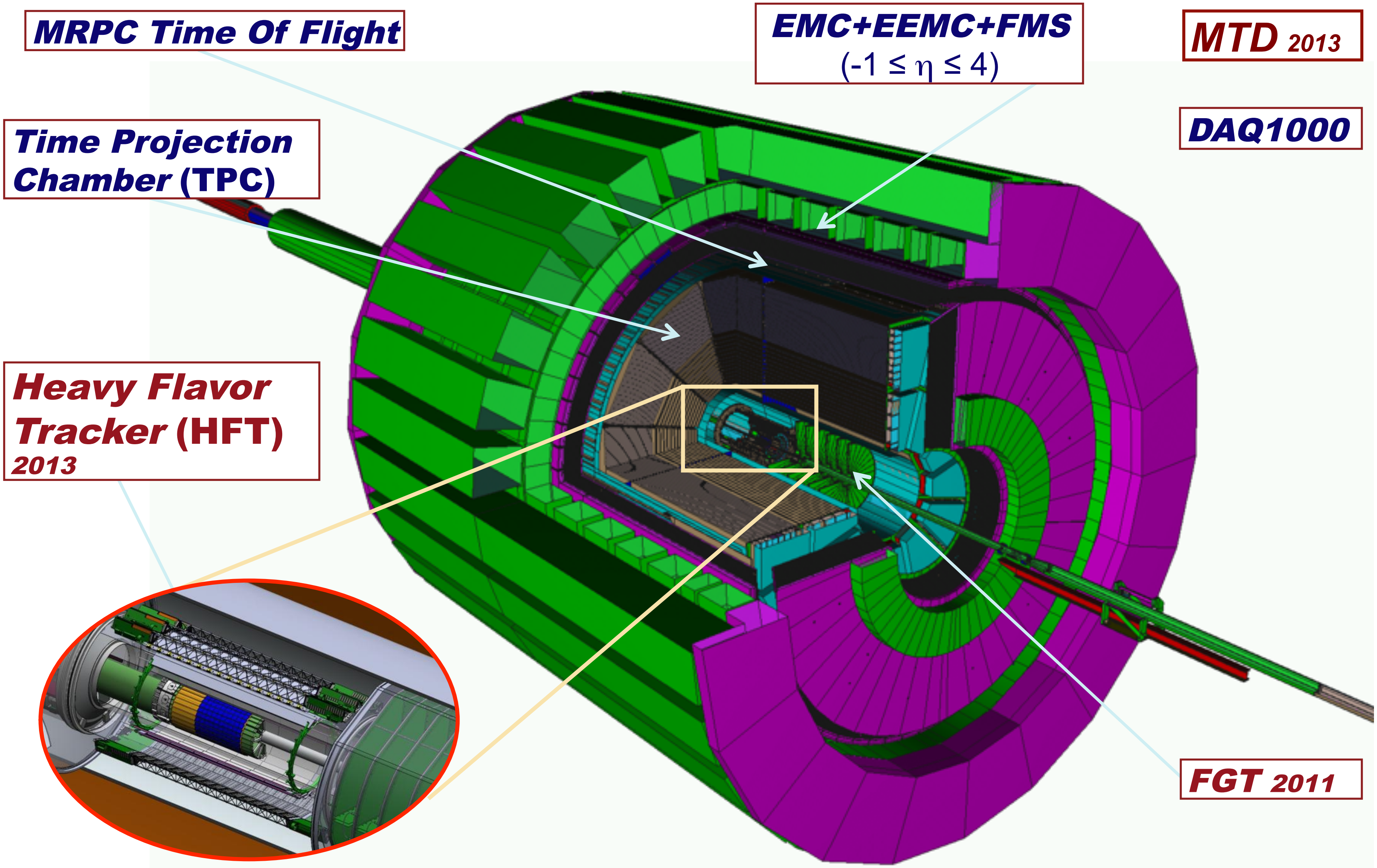
(2) RHIC Beam Energy Scan

- Status at STAR

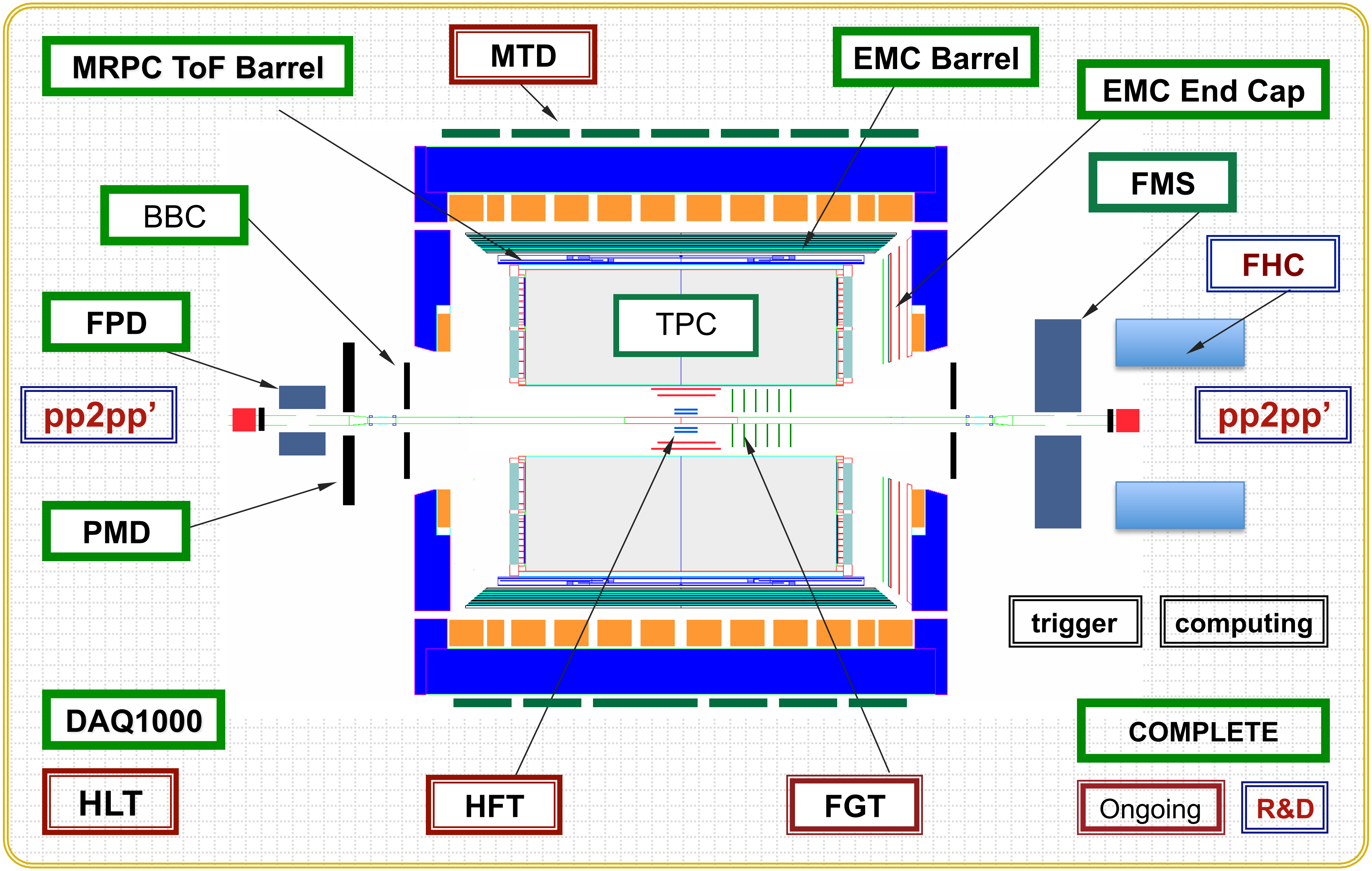
(3) Summary


STAR Collaboration

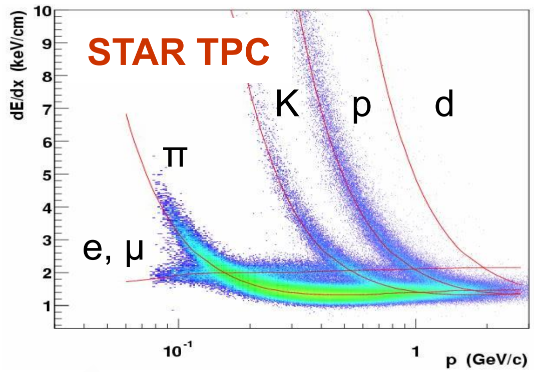
STAR Detectors *Fast and Full azimuthal particle identification*

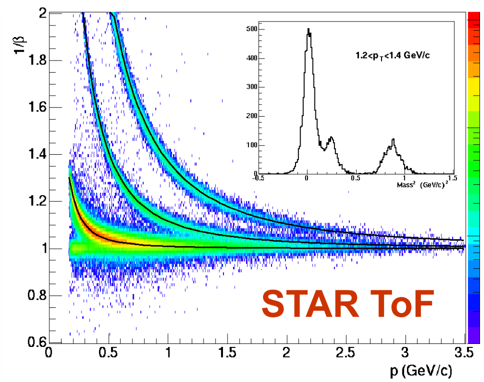


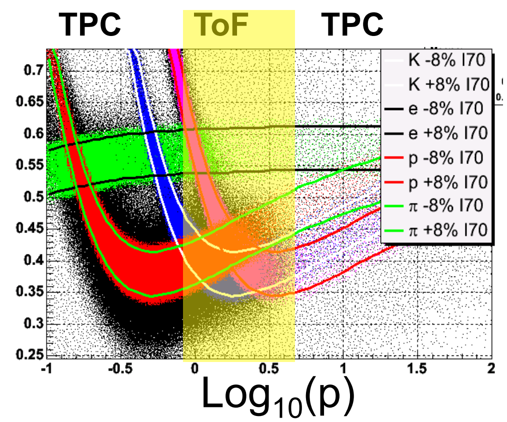
STAR Experiment

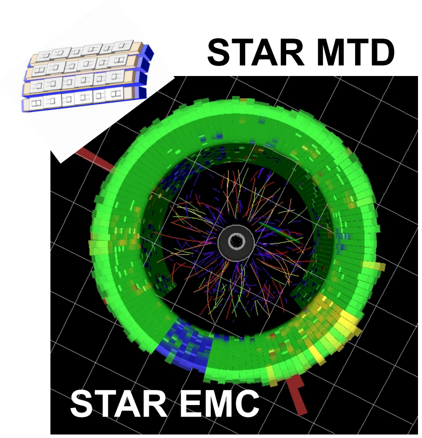


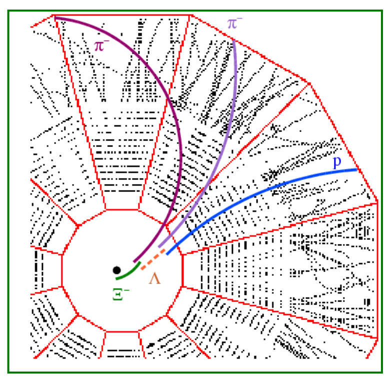
Particle Identification at STAR

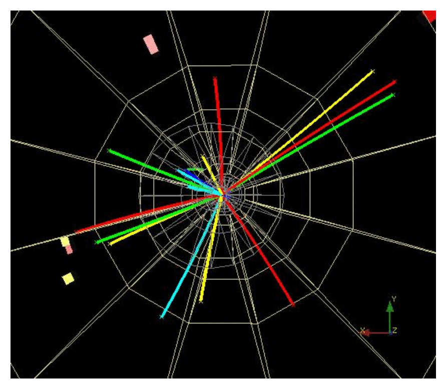


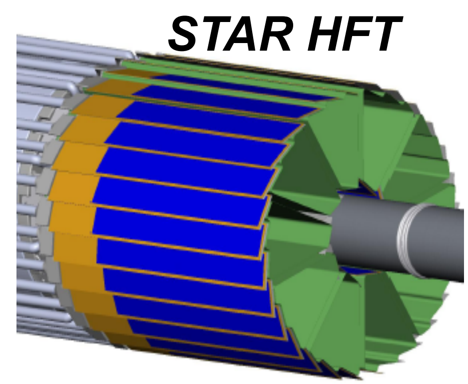








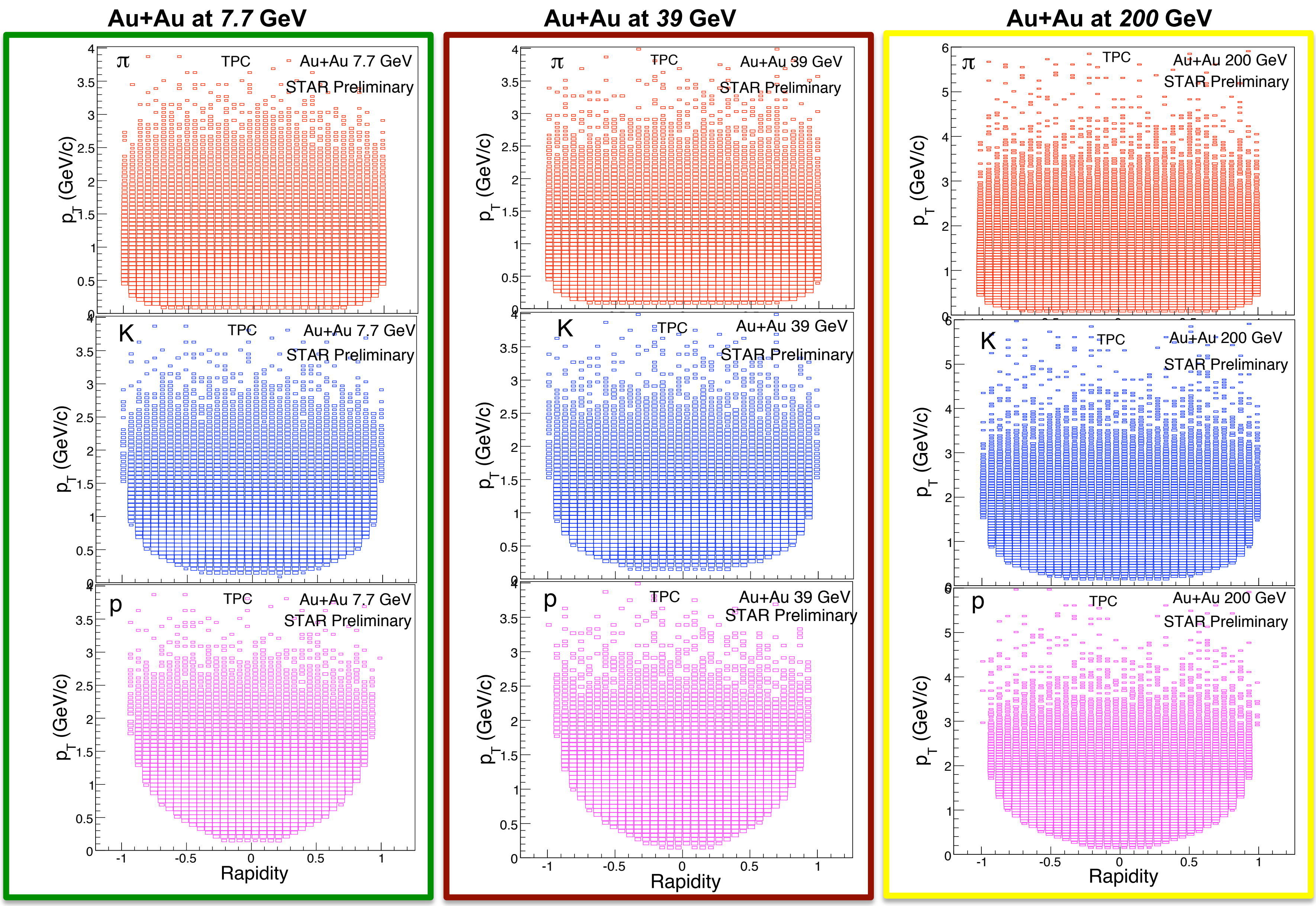




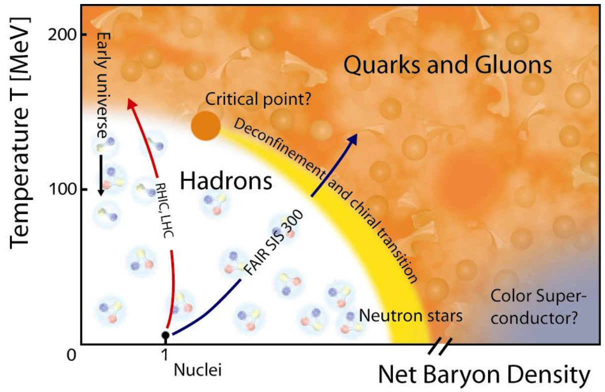
Neutral particles | **Strange hyperons** | **Jets** | **Heavy Quark Hadrons**

Multiple-fold correlations among the identified particles!

STAR PID: 7.7, 39, 200 GeV ($\pi^{\pm}$, $K^{\pm}$, p)

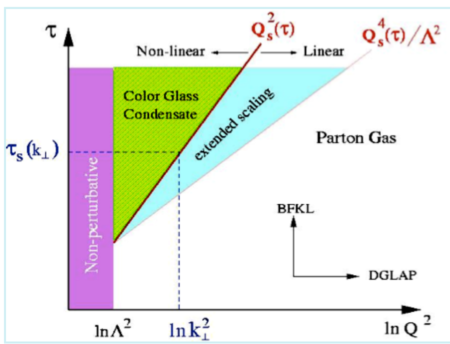


RHIC Physics Focus



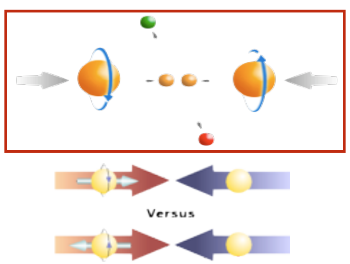
1) At 200 GeV at RHIC
- Study ***medium properties, EoS***
- pQCD in hot and dense medium

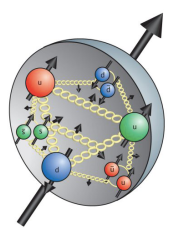
2) RHIC beam energy scan (BES)
- Search for the ***QCD critical point***
- Chiral symmetry restoration



Forward program
- Study low-x properties, initial condition, search for ***CGC***
- Study elastic and inelastic processes in pp2pp

2020 -
eRHIC
(eSTAR)





Polarized *p+p* program
- Study ***proton intrinsic properties***

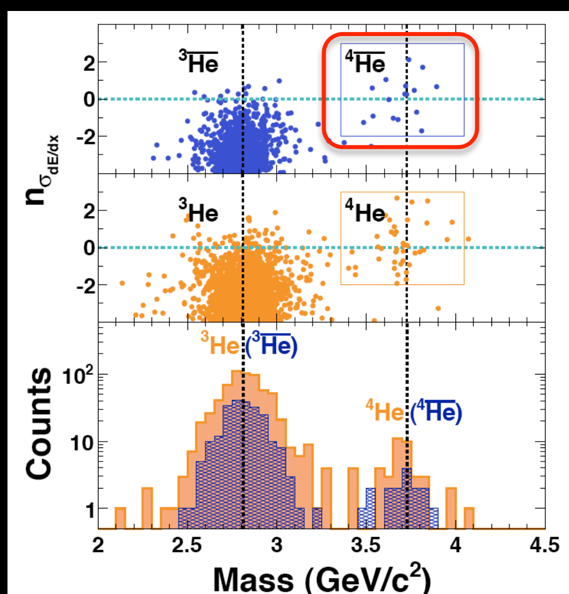
Antimatter Discoveries at RHIC

nature April, 2011

"Observation of the Antimatter Helium-4 Nucleus"

*by **STAR Collaboration***

***Nature**, 473, 353(2011).*

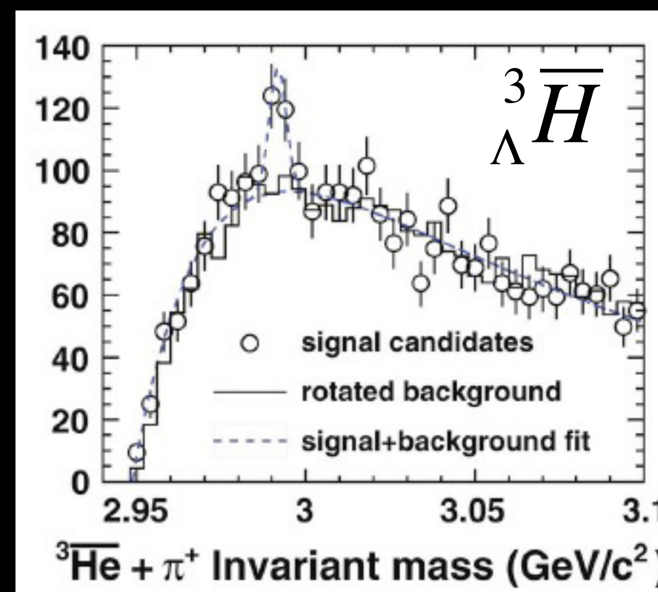


Science March, 2010

"Observation of an Antimatter Hypernucleus"

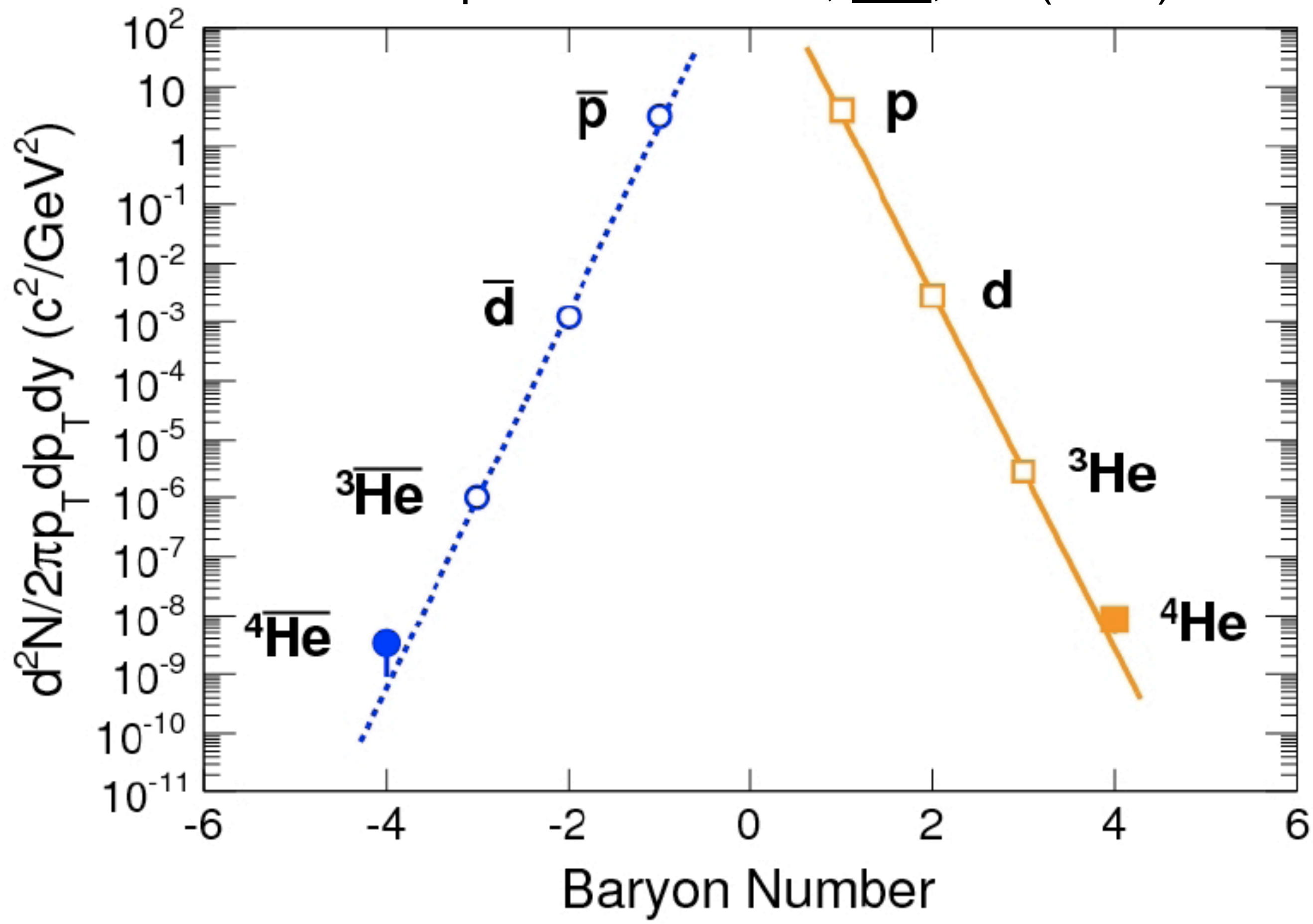
*by **STAR Collaboration***

***Science**, 328, 58(2010).*



Light Nuclei Productions at RHIC

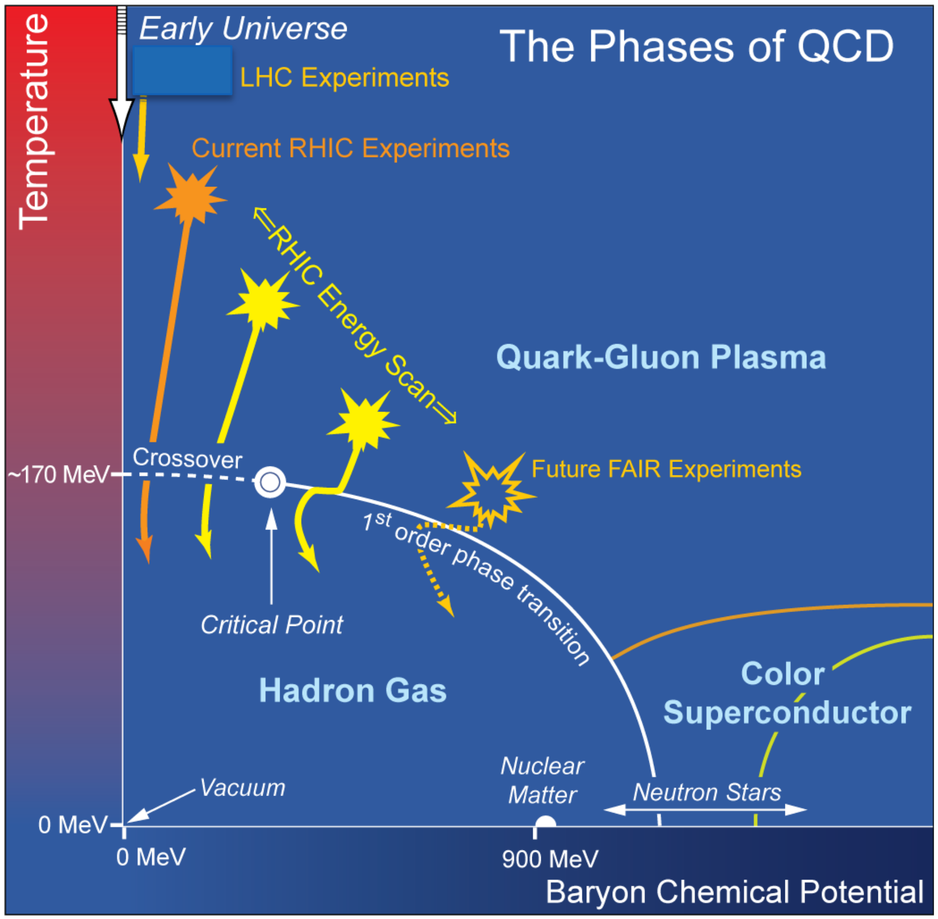
STAR Experiment: ***Nature***, **<u>473</u>**, 353(2011)



1) In high-energy nuclear collisions, **N(d) >> N(α)**:
   QGP ➔ (anti)light nuclei via coalescence
2) In the Universe, **N(d) << N(α): N(anti-α)?**

Beam Energy Scan at RHIC

Study QCD Phase Structure
- Signals of phase boundary
- Signals for critical point



Exp. Observations:

(1) v_2 - NCQ scaling:
partonic vs. hadronic dof

(2) Dynamical correlations:
partonic vs. hadronic dof

(3) Azimuthally HBT:
1^{st} order phase transition

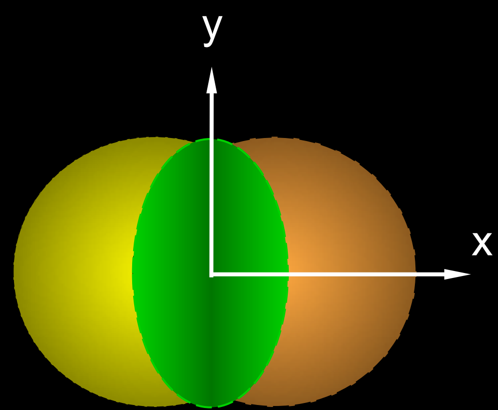
(4) Fluctuations:
Critical point, correl. Length
net-p, net-Q, … mixed ratios
C_2, C_4, C_6, C_8, …

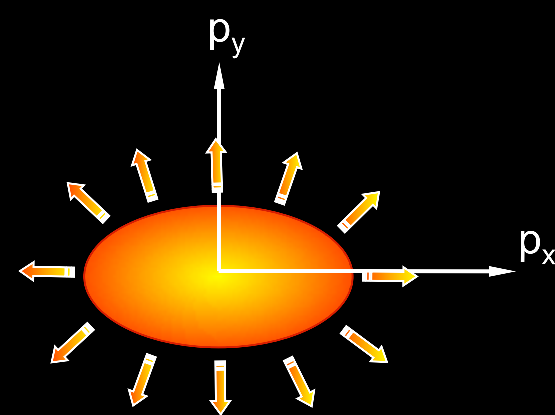
(5) Directed flow v_1
1^{st} order phase transition

- *http://drupal.star.bnl.gov/STAR/ starnotes/public/sn0493*
- *arXiv:1007.2613*

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇨ momentum-space-anisotropy

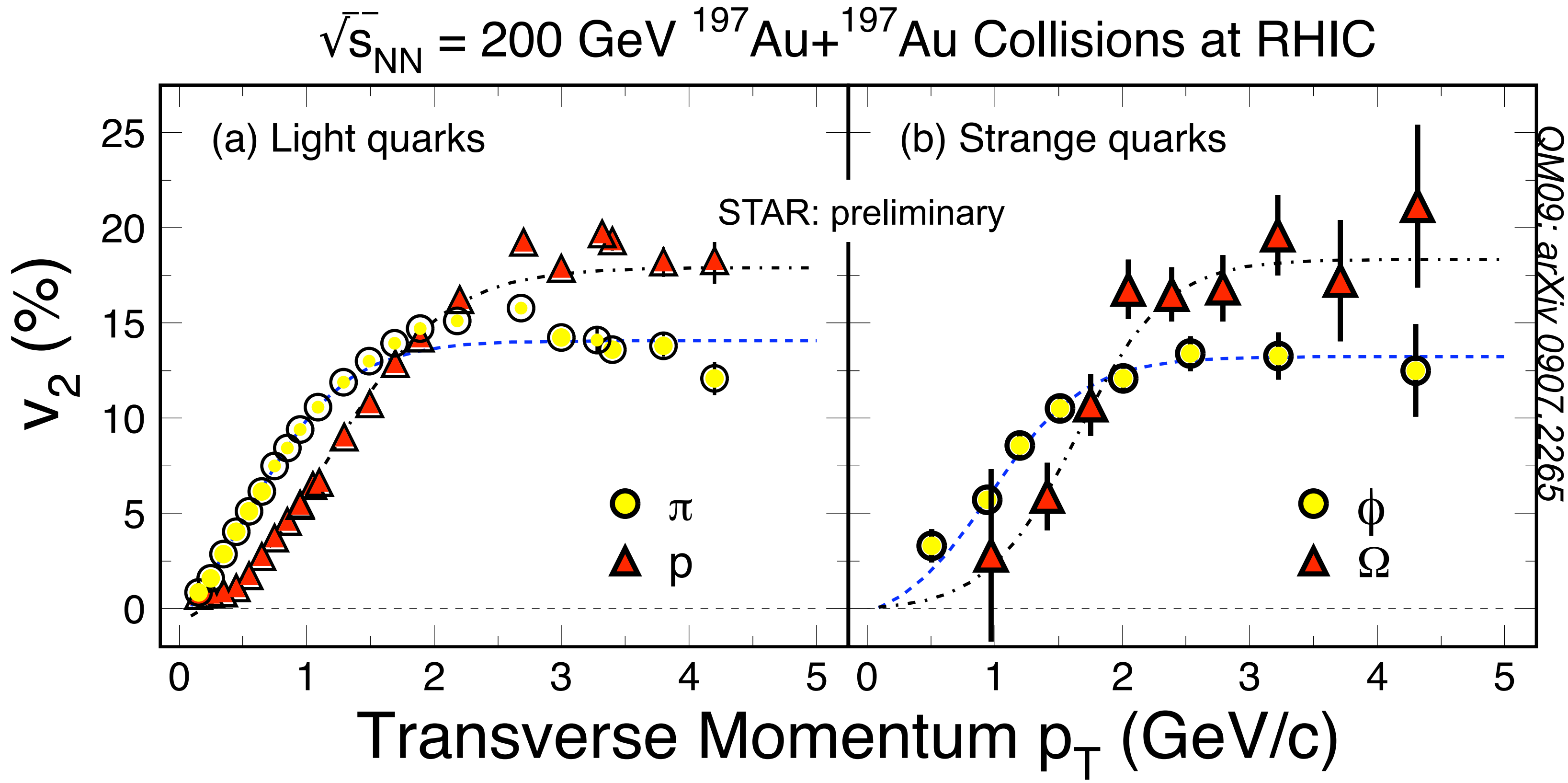




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

Partonic Collectivity at RHIC



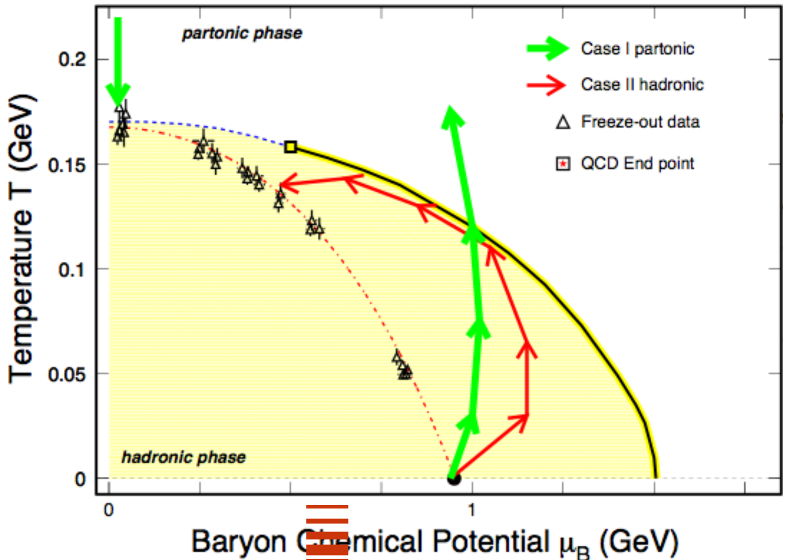
Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering

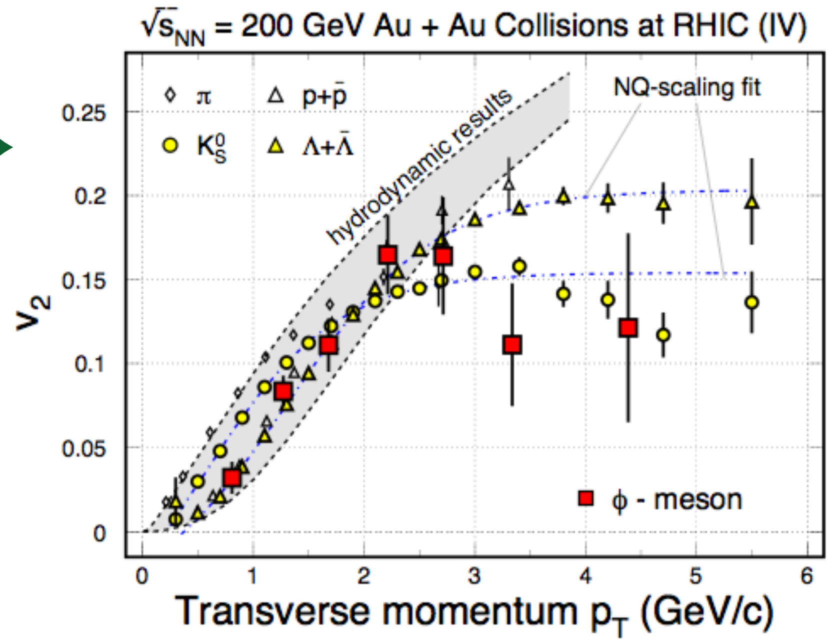
High p_T (> 2 GeV/c): ***number of quarks scaling***

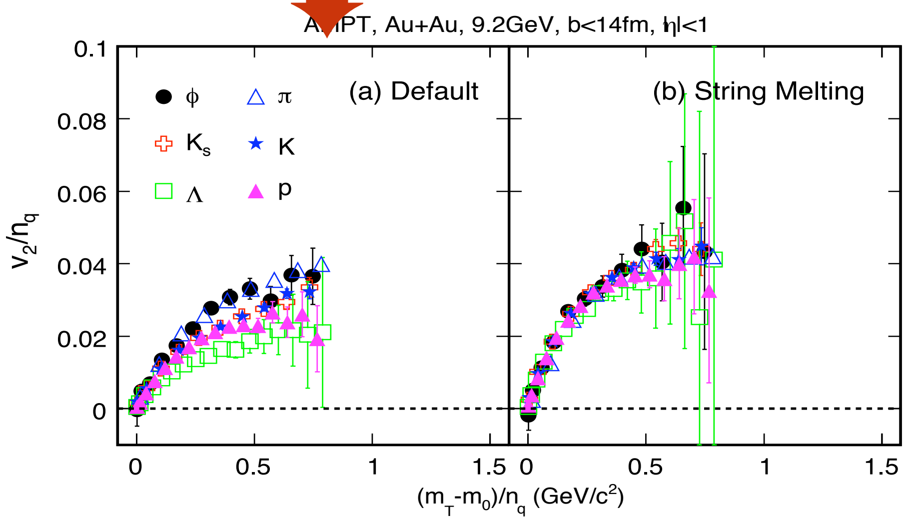
➔ ***Partonic Collectivity, necessary for QGP!***

➔ ***De-confinement in Au+Au collisions at RHIC!***

Observable*: NCQ Scaling in v_2







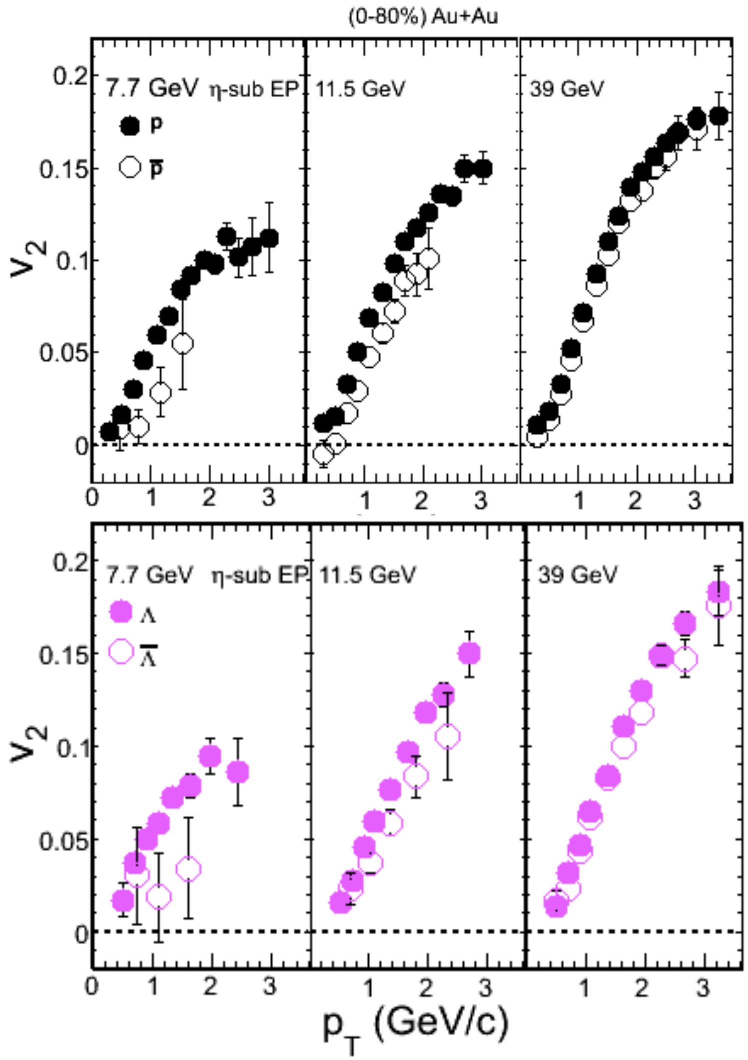
STAR Collaboration: F. Liu, S.S. Shi, K.J. Wu et al.

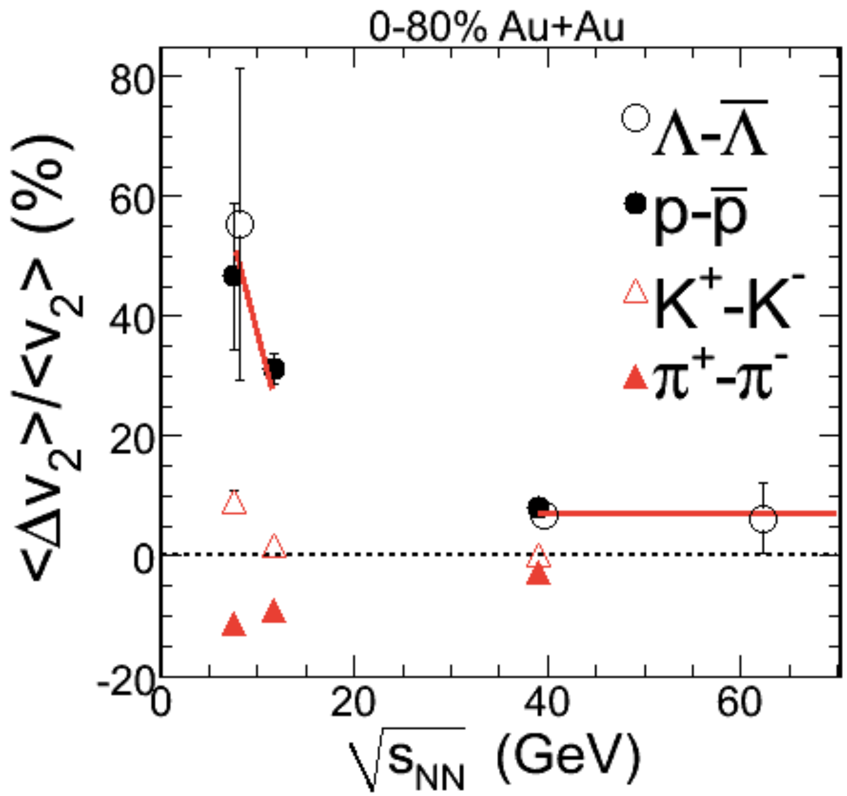
- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi, \pi\pi}$

In the hadronic case, no number of quark scaling and the value of v_2 of φ will be small.

*** Thermalization is assumed!**

(anti-)Particle v_2 vs. $\sqrt{s_{NN}}$





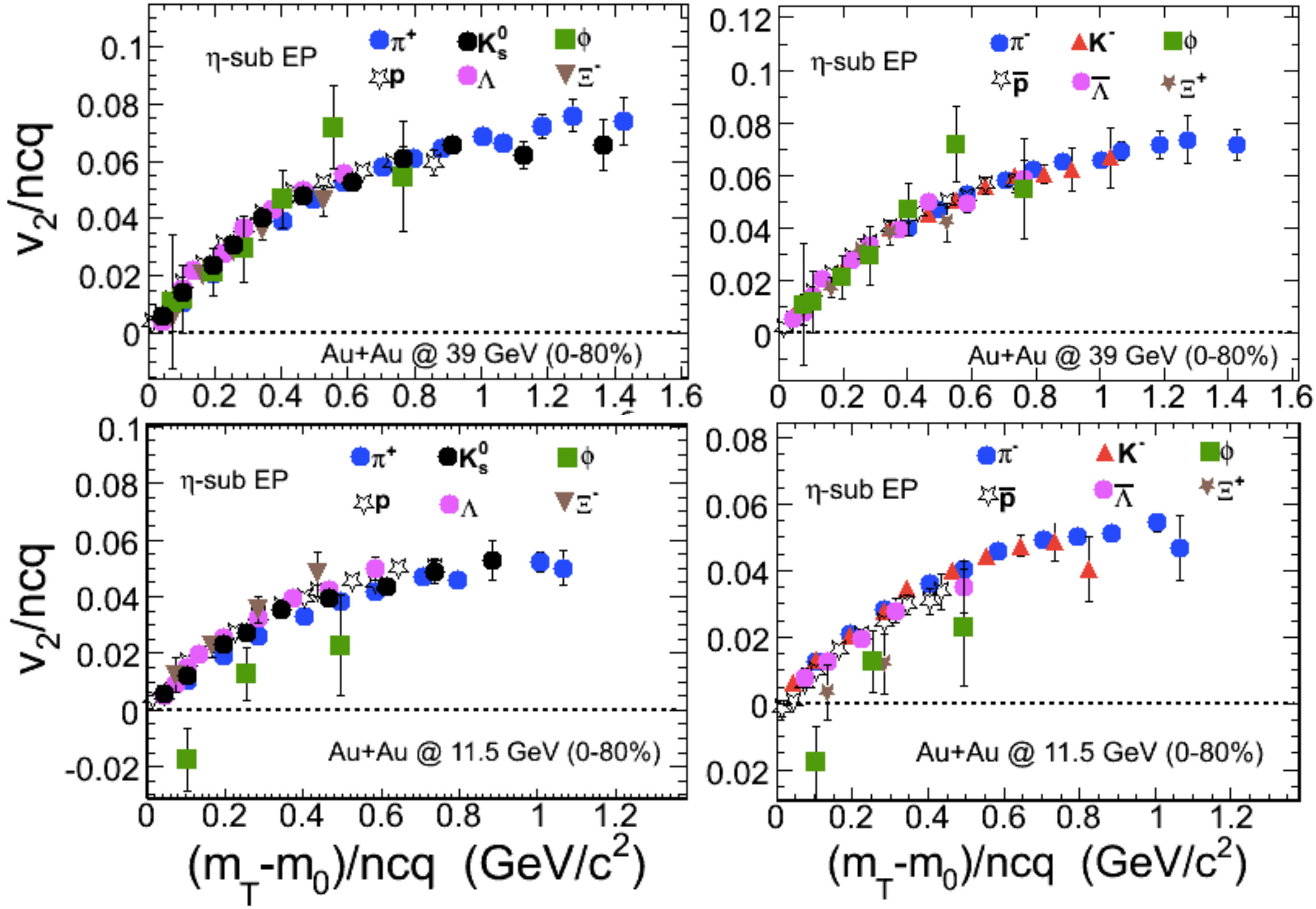
At $\sqrt{s_{NN}} \leq$ *11.5 GeV:*

- v_2(baryon) > v_2(anti-baryon)
- $v_2(\pi^+) < v_2(\pi^-)$
- $v_2(K^-) < v_2(K^+)$

STAR: Quark Matter 2011

Hadronic interactions appear dominant

ϕ-meson v_2 vs. $\sqrt{s_{NN}}$



- The φ-meson v_2 falls off trend from other hadrons at 11.5 GeV
- An effect of 2.6σ

Summary I: NCQ-Scaling in v_2

1) Partonic collectivity in 200 GeV collisions

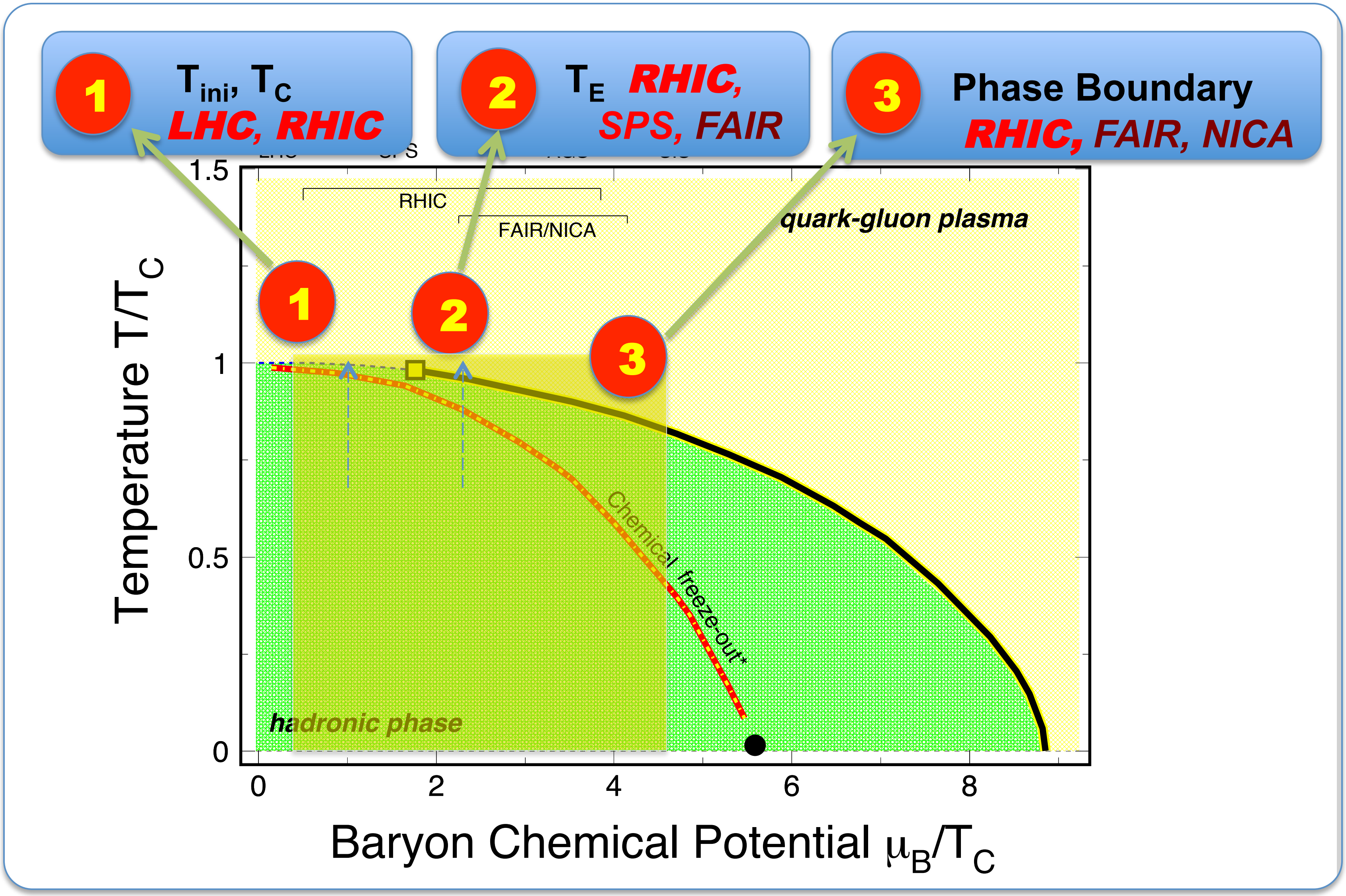
2) At $\sqrt{s_{NN}} \leq 11.5$ *GeV*

- v_2 scales for the same charged hadrons
- v_2(baryon) > v_2(anti-baryon)
- $v_2(\phi) < v_2$(hadron) (2.6σ)

➔ **$\sqrt{s_{NN}} \leq$ *11.5 GeV:* [hadronic dominant]**
$\sqrt{s_{NN}} \geq$ *39 GeV:* [partonic dominant]

Where is the critical point?

BES: (5400, 200, 62.4, 39, 27, 19.6, 15.5, 11.5, 7.7: 8 – 1 GeV)



Susceptibilities and Moments

Thermodynamic function:

$$\frac{p}{T^4} = \frac{1}{\pi^2}\sum_i d_i (m_i/T)^2 K_2(m_i/T)\cosh[(B_i\mu_B + S_i\mu_S + Q_i\mu_Q)/T]$$

The susceptibility: $T^{n-4}\chi_q^{(n)} = \frac{1}{T^4}\frac{\partial^n}{\partial(\mu_q/T)^n} P\left(\frac{T}{T_C},\frac{\mu_q}{T}\right)\Big|_{T/T_C}, \qquad q = B, Q, S$

Conserved Quantum Number

$$\chi_q^{(1)} = \frac{1}{VT^3}\langle \delta N_q \rangle$$

$$\chi_q^{(2)} = \frac{1}{VT^3}\left\langle (\delta N_q)^2 \right\rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3}\left\langle (\delta N_q)^3 \right\rangle$$

$$\chi_q^{(4)} = \frac{1}{VT^3}\left(\left\langle (\delta N_q)^4 \right\rangle - 3\left\langle (\delta N_q)^2 \right\rangle^2\right)$$

$$\frac{T^2\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2$$

$$\frac{T\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma$$

Thermodynamic function ⇔ Susceptibility ⇔ Moments

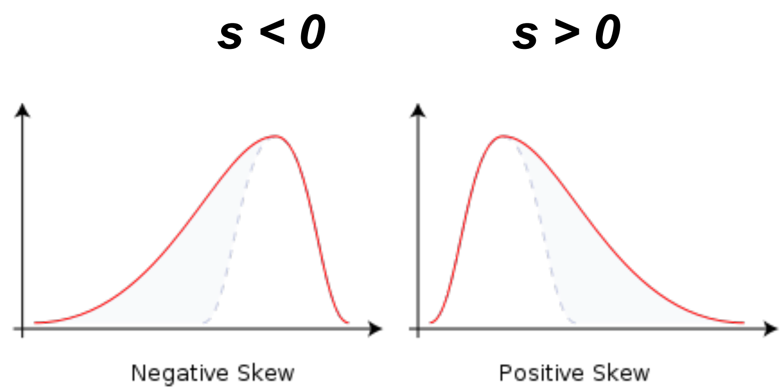
Model calculations, *e.g.* LGT, HRG ⇔ Measurements

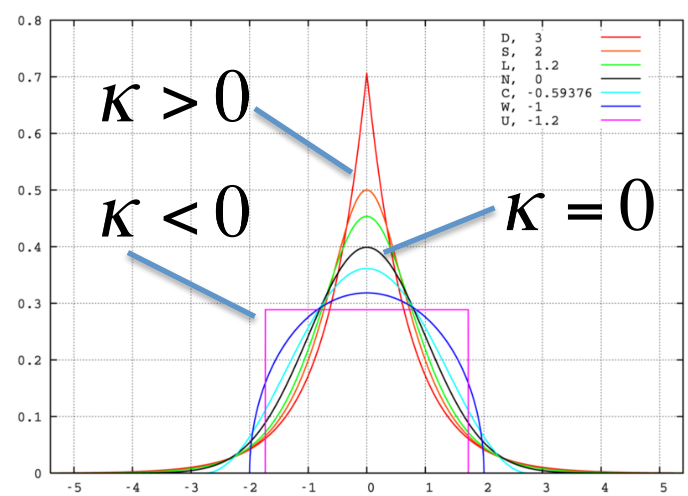
Non-Gaussian Fluctuations

N: event by event multiplicity distribution

$$m = \langle N \rangle \qquad s = \frac{\left\langle \left(N - \langle N \rangle\right)^3 \right\rangle}{\sigma^3}$$

$$\sigma = \sqrt{\left\langle \left(N - \langle N \rangle\right)^2 \right\rangle} \qquad \kappa = \frac{\left\langle \left(N - \langle N \rangle\right)^4 \right\rangle}{\sigma^4} - 3$$

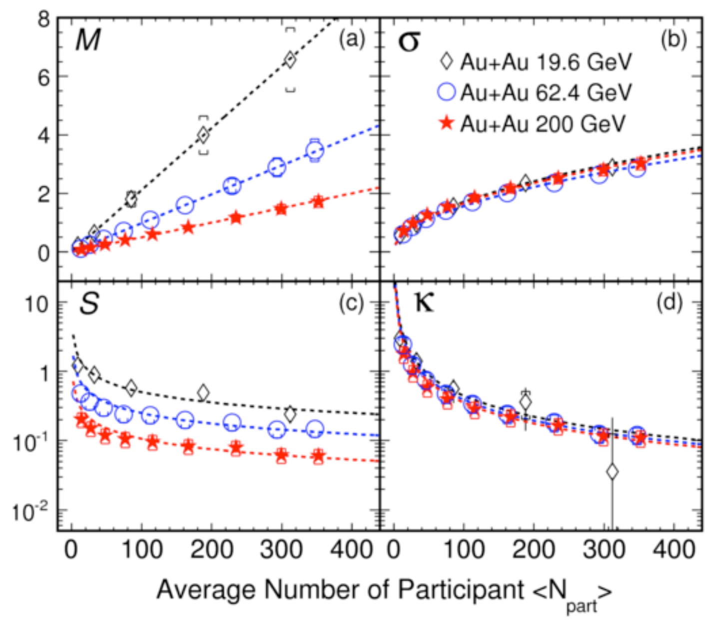


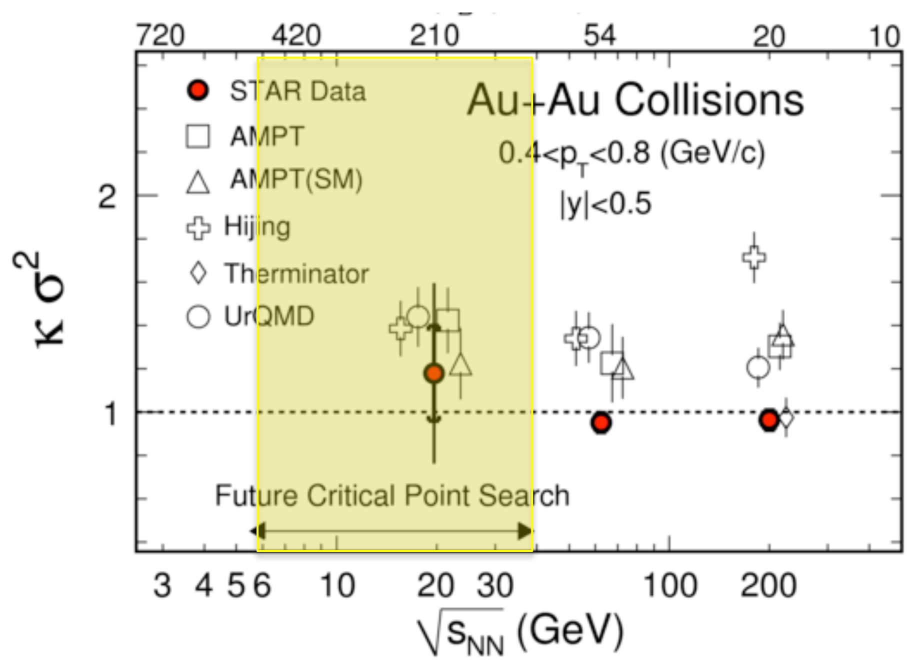


For a Gaussian distribution, the *s=0, κ=0.* **Ideal probe of the non-Gaussian fluctuations at critical point.**

Higher order correlations are correspond to higher power of the correlation length of the system: **more sensitive to critical phenomena**. Price: large number of events required.

High Moments of Net-protons



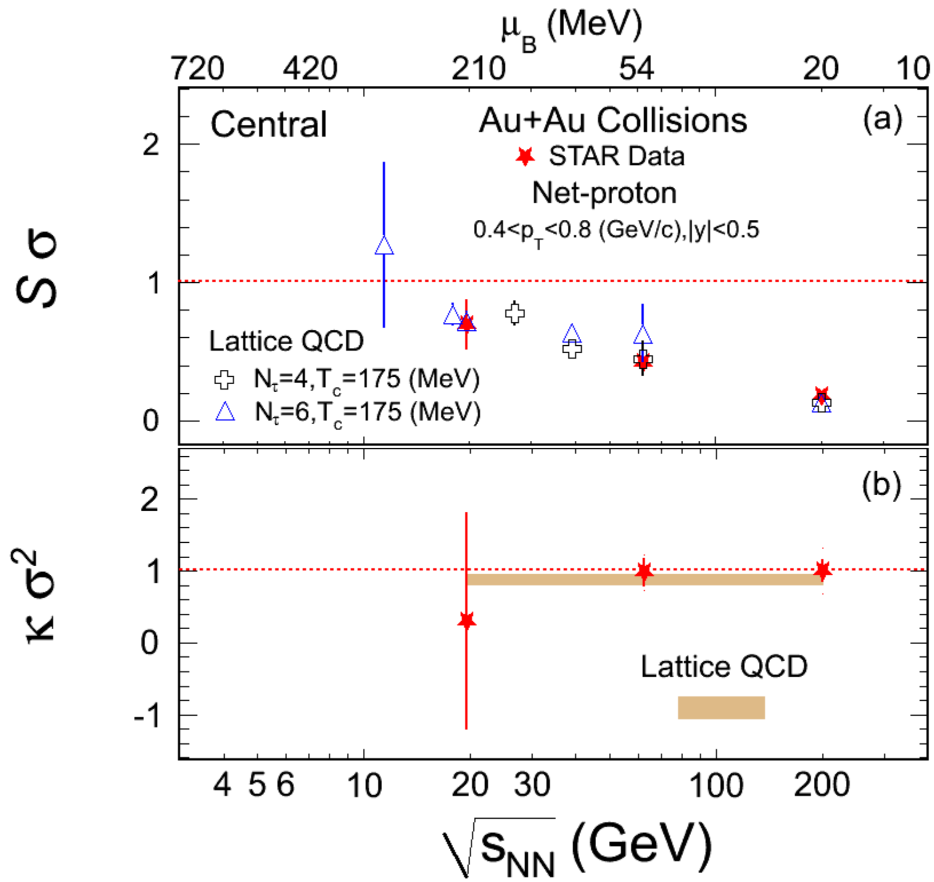


- Measure conserved quantities, ***B, s,*** *and* ***Q***.
- **First:** High order fluctuation results consistent with thermalization.
- **First:** Tests the *long distance QCD* predictions in hot/dense medium.

Caveats: (a) static vs. dynamic; (b) net-B vs. net-p; (c) potential effects of freeze-out…

- R. Gavai, S. Gupta, 1001. 3796 / F. Karsch, K. Redlich, 1007.2581 / M. Stephanov, 0911.1772.
- STAR: PRL105, 02232(2010) and references therein.

Comparing with LGT Results



References:
- STAR, *PRL105, 22303(10)*
- R.V. Gavai and S. Gupta: *PLB696, 459(11)*

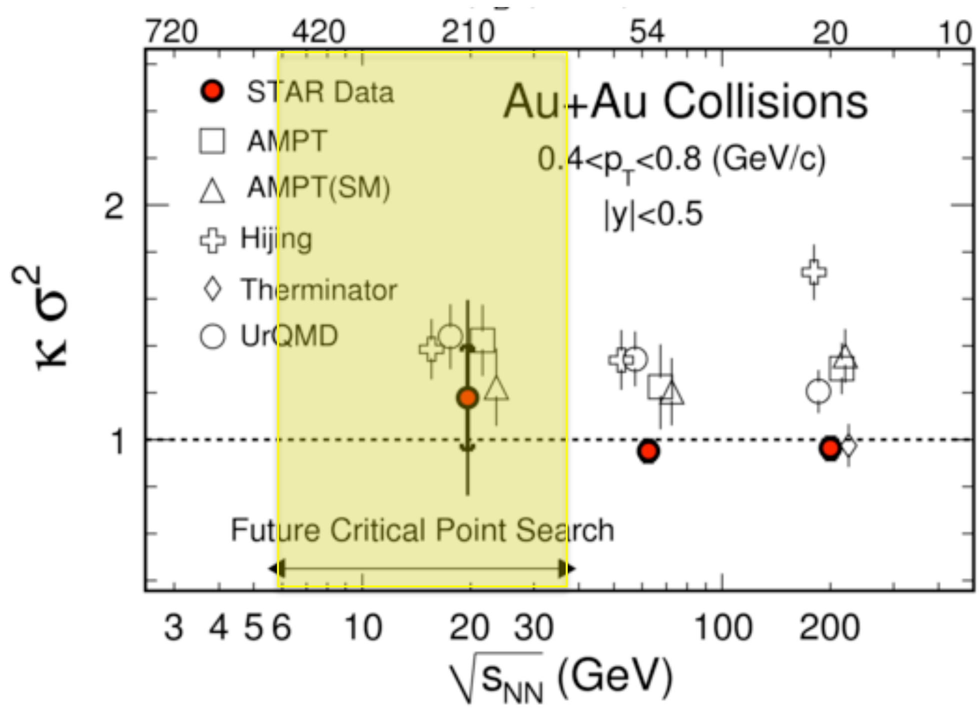
Assumptions:

(a) Freeze-out temperature is close to LGT T_C
(b) Thermal equilibrium reached in central collisions
(c) Taylor expansions, at $\mu_B \neq 0$, on LGT results are valid

➔ Lattice results are consistent with data for 60 < $\sqrt{s_{NN}}$ < 200 GeV

Remarks

STAR: *PRL, **105**, 22302(2010)*



Energy Scan in Au+Au collisions:

Run 10: 7.7, 11.5, 39 GeV
Run 11: 19.6, 27 GeV

1) Centrality averaged events. In this analysis, effects of volume and detecting efficiencies are all canceled out.

2) All transport model results values are higher than unity, except the Theminator result at 200GeV. LGT predicted values around 0.8-0.9, due to finite chemical potential.

3) Test of thermalization with higher moments.

4) **Critical point effect**: non-monotonic dependence on collision energy.

- STAR: PRL105, 22302(2010).
- F. Karsch and K. Redlich, arXiv:1007.2581

Effects of Centrality Bin Width

1) The fluctuation of the impact parameter led to the fluctuation in collision centrality

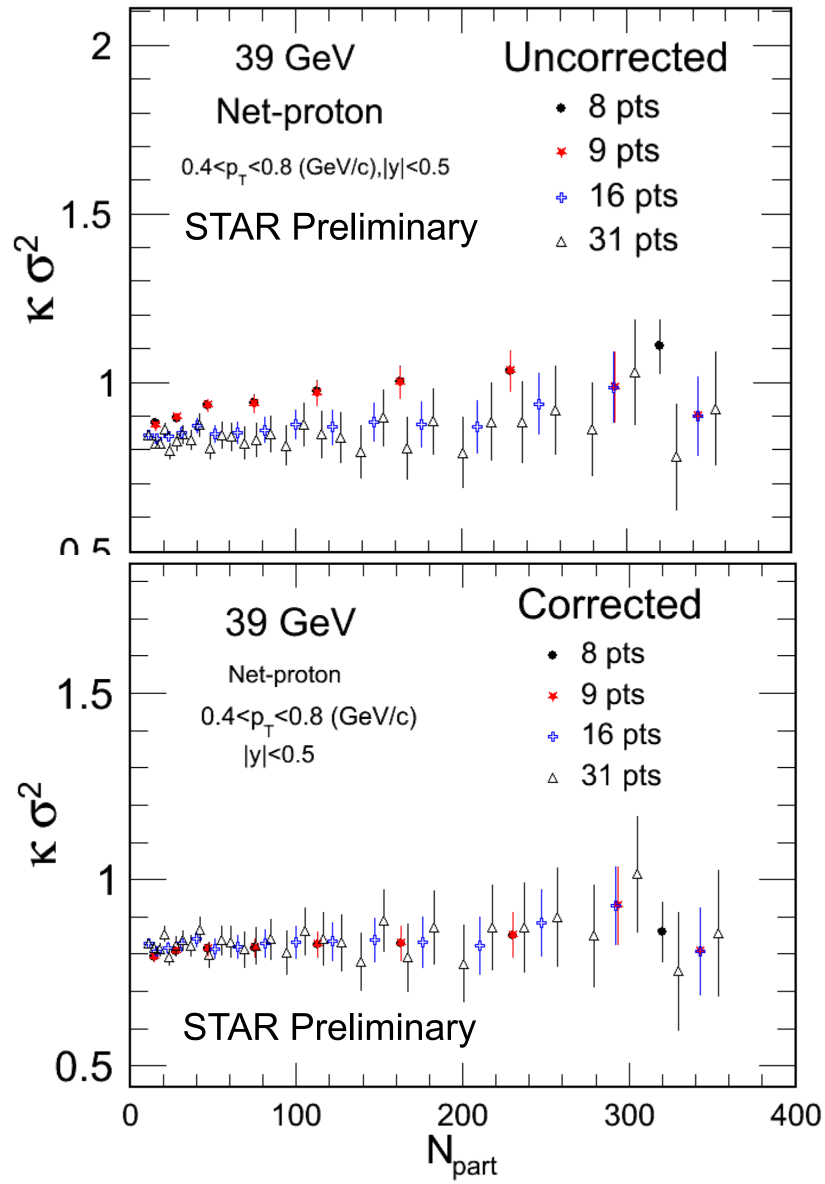
2) Multiplicity weighted moments help to remove the effect

$$h = \frac{\sum n_i h_i}{\sum n_i} = \sum \omega_i h_i$$

$i:$ *multiplicity*

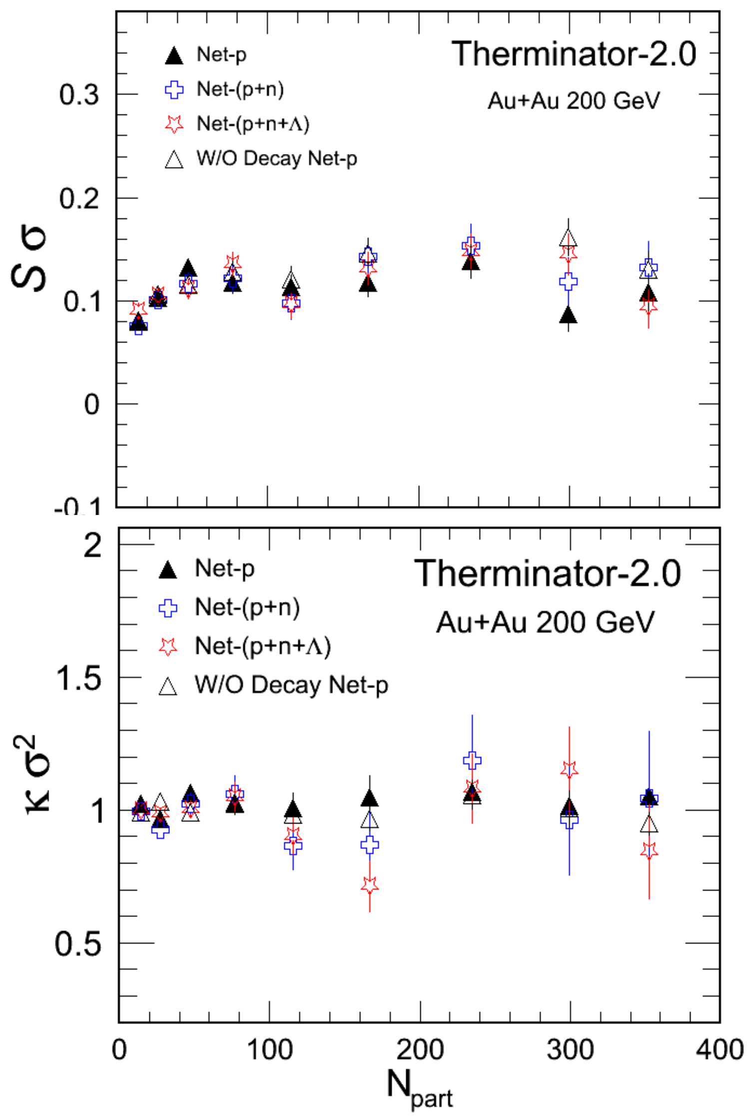
$h:$ $\sigma,\ S,\ \kappa$

STAR: SQM2011



Effects of Resonances, Neutrons

Therminator-2.0 (arXiv:1102.0273)



1) Resonance decay effect on the products of Sσ and $\kappa\sigma^2$ is small.

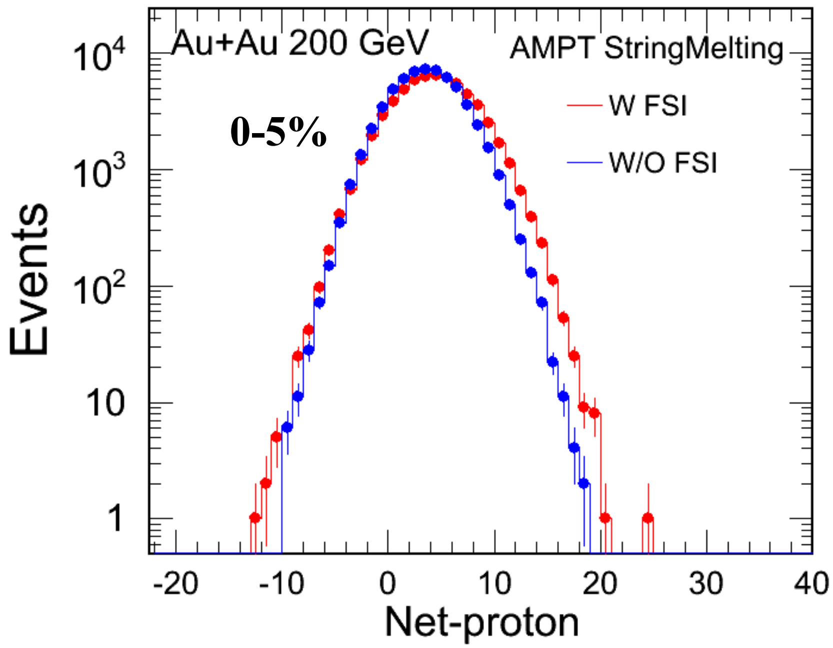
2) Inclusion of neutrons effects is small. Net-proton distributions reflect the net-baryon's.

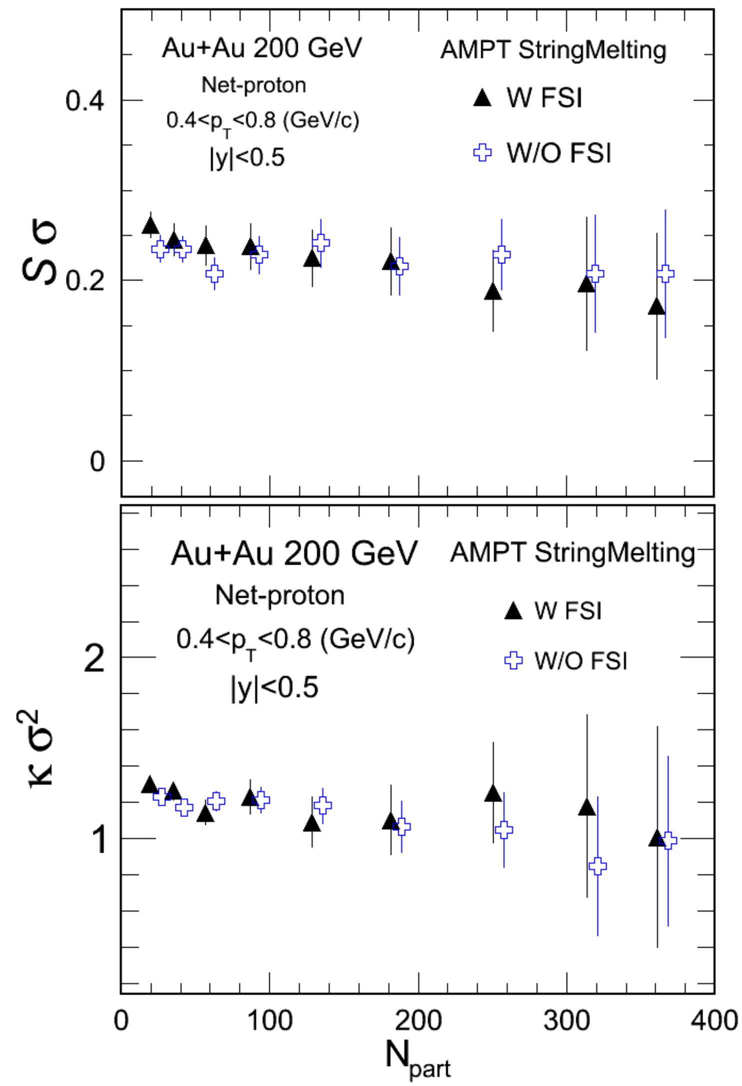
3) Low efficiency in the event-by-event measurements for hyperons.

STAR: SQM2011

Effects of the FSI

AMPT sm: Phys. Rev. C 72, 064901

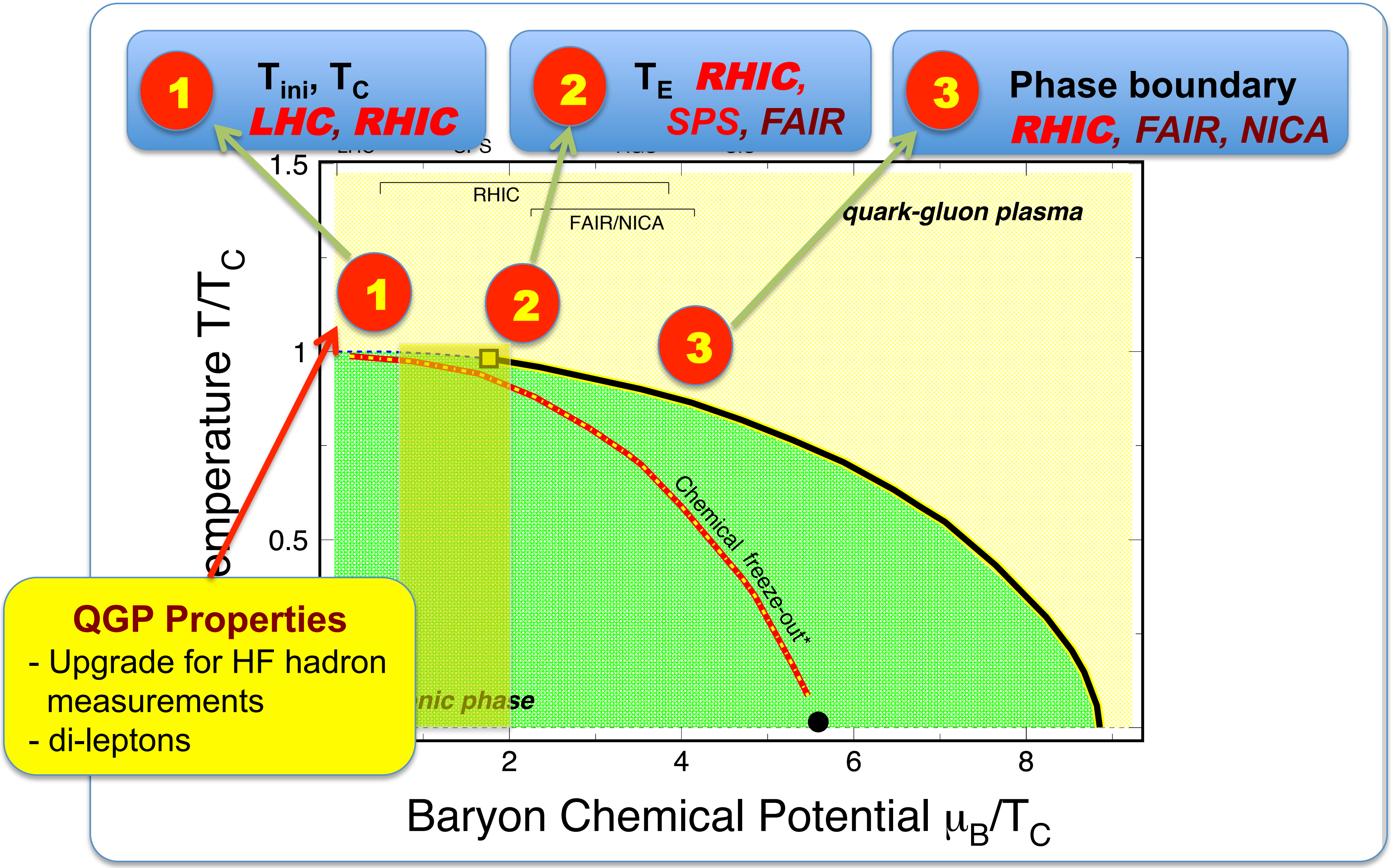




1) FSI effect: within errors, no effects
2) AMPT model used

STAR: SQM2011

RHIC: (7.7, 11.5, 15.5, 19.6, 27, 39,62, 200 GeV)



Summary

(1) In collisions at RHIC top energy, hot and dense ***matter, with partonic degrees of*** **freedom and collectivity, has been formed**

(2) RHIC BES: Preliminary results indicate

μ_B < *110 (MeV)*: **partonic interactions dominant**

μ_B > *320* (MeV): **hadronic interactions dominant**

(3) Near future physics program:

- BES: 'Comb' the QCD phase diagram;
  Complete analysis for 7.7/11.5/**15.5**(?)/19.6/27/39 GeV and 200 GeV, e.g. C_6, C_8, …;

- Heavy flavor, di-lepton: study QGP properties